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Charm System Tests of CPT and Lorentz Invariance with FOCUS

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We have performed a search for CPT violation in neutral charm meson oscillations. While flavor mixing in the charm sector is predicted to be small by the Standard Model, it is still possible to investigate CPT violation through a study of the proper time dependence of a CPT asymmetry in right-sign decay rates for $D^0 \to K^-\pi^+$ and $\overline{D}^0 \to K^+\pi^-$. This asymmetry is related to the CPT violating complex parameter ξ and the mixing parameters x and y: $A_{CPT} \propto \mathrm{Re}\,\xi\, y - \mathrm{Im}\,\xi\, x$. Our 95% confidence level limit is $-0.0068 < \mathrm{Re}\,\xi\, y - \mathrm{Im}\,\xi\, x < 0.0234$. Within the framework of the Standard Model extension incorporating CPT violation, we also find 95% confidence level limits for the coefficients of Lorentz violation of $(-3.7 < \Delta a_0 + 0.6\,\Delta a_Z < 6.5) \times 10^{-13}$ GeV, $(-9.4 < \Delta a_X < 5.0) \times 10^{-13}$ GeV, and $(-9.3 < \Delta a_Y < 5.1) \times 10^{-13}$ GeV, assuming the mixing parameters x and y are 1% and the DCS to CF relative strong phase is 15°.

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The combined symmetry of charge conjugation (C), parity (P), and time reversal (T) is believed to be respected by all local, point-like, Lorentz covariant field theories, such as the Standard Model. However, extensions to the Standard Model based on string theories do not necessarily require CPT invariance, and observable effects at low-energies may be within reach of experiments studying flavor oscillations [1]. A parametrization [2] in which CPT and T violating parameters appear has been developed which allows experimental investigation in many physical systems including atomic systems, Penning traps, and neutral meson systems [3]. Using this parameterization we present the first experimental results for CPT violation in the charm meson system.

Searches for CPT violation have been made in the neutral kaon system. Using an earlier CPT formalism [4], KTeV reported a bound on the CPT figure of merit $r_K \equiv |m_{K^0} - m_{\overline{K}^0}|/m_{K^0} < (4.5 \pm 3) \times 10^{-19}$ [5].

A more recent analysis, using framework [2] and more data extracted limits on the coefficients for Lorentz violation of $\Delta a_X, \Delta a_Y < 9.2 \times 10^{-22}$ GeV [6]. CPT tests in B^0 meson decay have been made by OPAL at LEP [7], and by Belle at KEK which has recently reported $r_B \equiv |m_{B^0} - m_{\overline{B}^0}|/m_{B^0} < 1.6 \times 10^{-14}$ [8].

To date, no experimental search for CPT violation has been made in the charm quark sector. This is due in part to the expected suppression of $D^0 - \overline{D}^0$ oscillations in the Standard Model, and the lack of a strong mixing signal in the experimental data. Recent mixing searches include a study of lifetime differences between charge-parity (CP) eigenstates [9–11], a study of the time evolution of D^0 decays by CLEO [12] and a study of the doubly Cabibbo suppressed ratio ($R_{\rm DCS}$) for the decay $D^0 \to K^+\pi^-$ [13]. Even without knowledge of the mixing parameters, one can investigate CPT violation through a study of the time dependence of D^0 decays.

Time dependent decay probabilities into right-sign and wrong-sign decay modes (wrong sign is used here in the context of decays via mixing) for neutral mesons which express the CPT violation have been developed in a general parametrization [2]. For the decay of a D^0 to a right-sign final state f, the time dependent decay probability is:

$$\begin{aligned} P_f(t) &\equiv |\langle f|T|D^0(t)\rangle|^2 = \frac{1}{2}|F|^2 \exp(-\frac{\gamma}{2}t) \\ &\times [(1+|\xi|^2)\cosh\Delta\gamma t/2 + (1-|\xi|^2)\cos\Delta m t \\ &\quad -2\mathrm{Re}\,\xi\,\sinh\Delta\gamma t/2 - 2\mathrm{Im}\,\xi\,\sin\Delta m t]. \qquad (1) \end{aligned}$$

The time dependent probability for the decay of a $\overline{D}^0$ to a final state $\overline{f}$, $\overline{P}_{\overline{f}}(t)$, may be obtained by making the substitutions $\xi \to -\xi$ and $F \to \overline{F}$ in the above equation. $F = \overline{F}$ is strictly true if CP (CPT) is not directly violated, which experimental evidence suggests is very nearly true in charm decays. F represents the basic transition amplitude for the decay $D^0 \to f$, $\Delta\gamma$ and Δm are the differences in physical decay widths and masses for the propagating eigenstates and can be related to the usual mixing parameters $x = -2\Delta m/\gamma = \Delta M/\Gamma$, $y = \Delta\gamma/\gamma = \Delta\Gamma/2\Gamma$, and γ is the sum of the physical decay widths. The complex parameter ξ controls the CPT violation and is seen to modify the shape of the time dependent decay probabilities. Expressions for wrong-sign decay probabilities involve both CPT and T violation parameters which only scale the probabilities, leaving the shape unchanged. Using only right-sign decay modes, the following asymmetry can be formed,

$$A_{\rm CPT}(t) = \frac{\overline{P}_{\overline{f}}(t) - P_f(t)}{\overline{P}_{\overline{f}}(t) + P_f(t)}, \qquad (2)$$

which is sensitive to the CPT violating parameter ξ:

$$A_{\rm CPT}(t) = \frac{2\mathrm{Re}\,\xi\,\sinh\Delta\gamma t/2 + 2\mathrm{Im}\,\xi\,\sin\Delta m t}{(1+|\xi|^2)\cosh\Delta\gamma t/2 + (1-|\xi|^2)\cos\Delta m t}. \qquad (3)$$

Experiments show that x, y mixing values are small ($<$ 5%). Equation 3, for small x, y and t, reduces to:

$$A_{\rm CPT}(t) = (\mathrm{Re}\,\xi\; y - \mathrm{Im}\,\xi\; x)\;\Gamma\; t. \qquad (4)$$

In this paper we search for a CPT violating signal using data collected by the FOCUS Collaboration during an approximately twelve month time period in 1996 and 1997 at Fermilab. FOCUS is an upgraded version of the E687 spectrometer. Charm particles are produced by the interaction of high energy photons (average energy ≈ 180 GeV for triggered charm states) with a segmented BeO target. In the target region, charged particles are tracked by up to sixteen layers of microstrip detectors. These detectors provide excellent vertex resolution. Charged particles are further tracked by a system of five multi-wire proportional chambers and are momentum analyzed by two oppositely polarized large aperture dipole magnets. Particle identification is accomplished by three multi-cell threshold Čerenkov detectors [14], two electromagnetic calorimeters, an hadronic calorimeter and muon counters.

We analyze the two right-sign hadronic decays $D^0 \to K^-\pi^+$ and $\overline{D}^0 \to K^+\pi^-$. We use the soft pion from the decay $D^{*+} \to D^0\pi^+$ to tag the flavor of the D at production, and the kaon charge in the decay $D^0 \to K^-\pi^+$ to tag the D flavor at decay. $D^0 \to K^-\pi^+$ events are selected by requiring a minimum detachment ℓ of the secondary (decay) vertex from the primary (production) vertex of 5 σ_ℓ, where σ_ℓ is the calculated uncertainty of the detachment measurement. The primary vertex is found using a candidate driven vertex finder which nucleates tracks about a "seed" track constructed using the secondary vertex and the D momentum vector. Both primary and secondary vertices are required to have fit confidence levels greater than 1%. The D^*-tag is implemented by requiring the $D^* - D^0$ mass difference be within 3 MeV/c^2 of the nominal value [15]. A χ^2-like variable called $W_i \equiv -2\log(\text{likelihood})$, where i ranges over electron, pion, kaon and proton hypotheses is used for particle identification [14]. For the K and the π candidates we require W_i to be no more than four units greater than the smallest of the other three hypotheses ($W_i - W_{min} < 4$) which eliminates candidates that are likely to be mis-identified. In addition, D^0 daughters must satisfy the slightly stronger $K\pi$ separation criteria $W_\pi - W_K > 0.5$ for the K and $W_K - W_\pi > -2$ for the π. Doubly misidentified $D^0 \to K^-\pi^+$ is removed by imposing a hard Čerenkov cut on the sum of the two separations ($(W_\pi - W_K)_K + (W_K - W_\pi)_\pi > 8$). $K\pi$ pairs with highly asymmetrical momenta are more likely to be background than signal. A cut is made on the momentum asymmetry, $P_A = |(P_K - P_\pi)/(P_K + P_\pi)|$, to reject these candidates. The best background rejection is achieved by applying the cut in the following way, $P(D^0) > -160 + 280 \times P_A$, where $P(D^0), P_K$ and P_π are the momenta of the D and the daughter kaon and pion respectively. To avoid large acceptance corrections due to the presence of a trigger counter downstream of

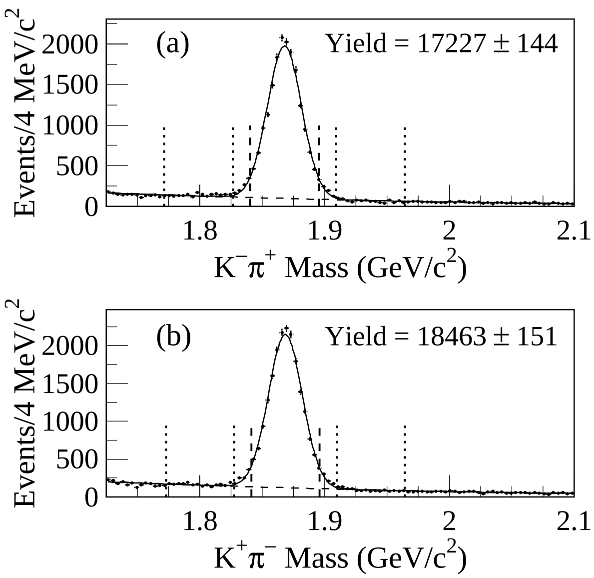

FIG. 1: Invariant mass of ($D^0 \to K^-\pi^+$ (a); $\overline{D}^0 \to K^+\pi^-$ (b)) for data (points) fitted with a Gaussian signal and quadratic background (solid line). The vertical dashed lines indicate the signal region, the vertical dotted lines indicate the sideband region.

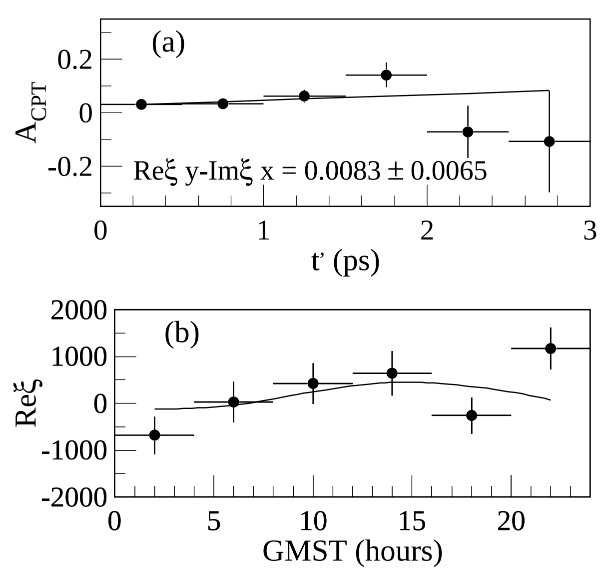

FIG. 2: (a) A_{CPT} as a function of reduced proper time. The data points represent the A_{CPT} as given in Eq. 5 and the solid line represent the fit given in functional form by Eq. 4; (b) $\mathrm{Re}\,\xi$ as a function of Greenwich Mean Sidereal Time (GMST).

the silicon detector, we impose a fiducial cut on the location of the primary vertex. Figure 1 shows the invariant mass distribution for D^*-tagged, right-sign decays $D^0 \to K^-\pi^+$ and $\overline{D}^0 \to K^+\pi^-$. Gaussian signal plus quadratic background fits yield $17\,227 \pm 144$ and $18\,463 \pm 151$ signal events, respectively. The proper time decay distribution is distorted by the imposition of a detachment cut between the primary and secondary vertices. The reduced proper time, defined as $t' = (\ell - N\sigma_\ell)/(\beta\gamma c)$ where ℓ is the distance between the primary and secondary vertex, σ_ℓ is the resolution on ℓ, and N is the minimum detachment cut applied, removes this distortion. A simulation study was done measuring the differences in measured values of A_{CPT} and ξ using t' in place of t in Eq. 5 and Eq. 4. The differences were found to be negligible compared to other systematic uncertainties.

We plot the difference in right-sign events between $\overline{D}^0$ and D^0 in bins of reduced proper time t'. For each data point, the background subtracted yields of right-sign D^0 and $\overline{D}^0$ are used in forming the ratio:

$$A_{\mathrm{CPT}}(t') = \frac{\overline{Y}(t') - Y(t')\frac{\overline{f}(t')}{f(t')}}{\overline{Y}(t') + Y(t')\frac{\overline{f}(t')}{f(t')}}, \tag{5}$$

where $\overline{Y}(t')$ and $Y(t')$ are the yields for $\overline{D}^0$ and D^0 and $\overline{f}(t')$, $f(t')$ are their respective correction functions. The functions $\overline{f}(t')$ and $f(t')$ account for geometrical acceptance, detector and reconstruction efficiencies, and absorption of parent and daughter particles. The correction functions are determined using a detailed Monte Carlo (MC) simulation of the experiment where the production (using PYTHIA [16]) was tuned so that the production distributions for data and MC matched. The shapes of the $f(t')$ and $\overline{f}(t')$ functions are obtained by dividing the reconstructed MC t' distribution by a pure exponential with the MC generated lifetime. The ratio of the correction functions enters explicitly in Eq. 5 and its effects on the asymmetry are less than 1.3%. The FOCUS data contains more $\overline{D}^0$ than D^0 decays due to production asymmetry [17]. The effect on the A_{CPT} distribution is to add a constant offset, which is accounted for in the fit. The A_{CPT} data in Fig. 2(a) are fit to a line using the form of Eq. 4 plus a constant offset. The result of the fit is $\mathrm{Re}\,\xi\; y - \mathrm{Im}\,\xi\; x = 0.0083 \pm 0.0065$.

In the CPT and Lorentz violating extension to the Standard Model proposed by Kostelecký at al. [18], the CPT violating parameter ξ can depend on lab momentum, spatial orientation, and sidereal time [2, 19]. Coefficients of Lorentz violation depend on the flavor of the valence quark states. For this reason CPT violation in the K, D, and B systems need not be the same. In the case of FOCUS, a forward, fixed-target spectrometer, the ξ parameter assumes the following form [2]:

$$\begin{aligned}\xi(\hat{t},p) \;=\; & \frac{\gamma(p)}{\Delta\lambda}[\Delta a_0 + \beta\Delta a_Z \cos\chi \\ & +\beta\sin\chi(\Delta a_Y \sin\Omega\hat{t} + \Delta a_X \cos\Omega\hat{t})],\end{aligned} \tag{6}$$

where Ω and $\hat{t}$ are the sidereal frequency and time respectively, X, Y, Z are non-rotating coordinates with Z aligned along the Earth's rotation axis, $\Delta\lambda = (x - iy)/\tau$ (τ is the mean D^0 lifetime), and $\gamma(p) = \sqrt{1 + P_{D^0}^2/m_{D^0}^2}$. Since Eq. 6 requires $\mathrm{Re}\,\xi\, y - \mathrm{Im}\,\xi\, x = 0$, setting limits on the coefficients of Lorentz violation requires expanding the asymmetry in Eq. 3 to higher (non-vanishing) terms. In addition, the interference term of right-sign decays with the doubly Cabibbo suppressed (DCS) decays must also be included since it gives a comparable contribution. The asymmetry can be written as:

$$A_{\rm CPT} = \frac{{\rm Re}\,\xi(x^2+y^2)(t/\tau)^2}{2x} \left[\frac{xy}{3}(t/\tau) + \sqrt{R_{\rm DCS}}\,(x\,\cos\delta + y\,\sin\delta)\right], \quad (7)$$

where $R_{\rm DCS}$ is the branching ratio of DCS relative to right-sign decays and δ is the strong phase between the DCS and right-sign amplitudes. We searched for a sidereal time dependence [22] by dividing our data sample into four-hour bins in Greenwich Mean Sidereal Time (GMST) [20] and repeating our fits using the asymmetry given by Eq. 7. The resulting distribution, shown in Fig. 2(b), was fit using Eq. 6 and the results for the coefficients of Lorentz violation were $\Delta a_0 + 0.6\,\Delta a_Z = (1.4 \pm 1.5) \times 10^{-13}$ GeV, $\Delta a_X = (-2.2 \pm 2.7) \times 10^{-13}$ GeV, and $\Delta a_Y = (-2.1 \pm 2.6) \times 10^{-13}$ GeV. The angle between the FOCUS spectrometer axis and the Earth's rotation axis is approximately $\chi = 53°(\cos\chi = 0.6)$. We average over all D^0 momentum so $\langle\gamma(p)\rangle \approx \gamma(\langle p\rangle) = 39$ and $\beta = 1$. We assume $x = 1\%$, $y = 1\%$, and $\delta = 15°$ [23].

Previous analyses have shown that MC absorption corrections are very small [9]. The interactions of pions and kaons with matter have been measured but no equivalent data exists for charm particles. Several variations from our standard absorption simulation were considered. The standard deviation of these variations returns systematic uncertainties of ± 0.0017, $\pm 0.4 \times 10^{-13}$ GeV, $\pm 0.0 \times 10^{-13}$ GeV, and $\pm 0.1 \times 10^{-13}$ GeV to our measurements of ${\rm Re}\,\xi\ y - {\rm Im}\,\xi\ x$, $\Delta a_0 + 0.6\,\Delta a_Z$, Δa_X, and Δa_Y respectively.

We also investigated parent (D^0,$\overline{D}^0$) and daughter (K,π) absorption separately. The study showed that the flat corrections in MC are small not only because absorption effects are small but also because of a cancellation due to two competing effects. The D^0 has a slightly higher absorption rate than the $\overline{D}^0$, and the net absorption rate of a (K^-,π^+) from a D^0 is slightly lower than the net absorption rate of a (K^+,π^-) from the $\overline{D}^0$.

In a manner similar to the S-factor method used by the Particle Data group PDG [15] we made eight statistically independent samples of our data in order to look for systematic effects. We split the data in four momentum ranges and two years. The split in year was done to look for effects associated with target geometry and reconstruction due to the addition of four silicon planes near the targets in January, 1997 [21]. We found no contribution to our measurements of ${\rm Re}\,\xi\ y - {\rm Im}\,\xi\ x$ and $\Delta a_0 + 0.6\,\Delta a_Z$. The contributions for Δa_X and Δa_Y were $\pm 1.7 \times 10^{-13}$ GeV and $\pm 2.2 \times 10^{-13}$ GeV respectively. We also varied the bin widths and the position of the sidebands to check the stability of the fits. The standard deviation of these variations returns systematic uncertainties of ± 0.0012, $\pm 0.4 \times 10^{-13}$ GeV, $\pm 1.2 \times 10^{-13}$ GeV, and $\pm 0.7 \times 10^{-13}$ GeV to our measurements of ${\rm Re}\,\xi\,y - {\rm Im}\,\xi\,x$, $\Delta a_0 + 0.6\,\Delta a_Z$, Δa_X, and Δa_Y respectively. Finally, we varied our ℓ/σ_ℓ and $W_\pi - W_K$ requirements and the standard deviation of these variations returns systematic uncertainties of ± 0.0036, $\pm 2.0 \times 10^{-13}$ GeV, $\pm 1.4 \times 10^{-13}$ GeV, and $\pm 1.4 \times 10^{-13}$ GeV to our measurements of ${\rm Re}\,\xi\ y - {\rm Im}\,\xi\ x$, $\Delta a_0 + 0.6\,\Delta a_Z$, Δa_X, and Δa_Y respectively. Contributions to the systematic uncertainty are summarized in Table I and Table II. Taking contributions to be uncorrelated we obtain a total systematic uncertainty of ± 0.0041 for ${\rm Re}\,\xi\,y - {\rm Im}\,\xi\,x$, $\pm 2.1 \times 10^{-13}$ GeV for $\Delta a_0 + 0.6\,\Delta a_Z$, $\pm 2.5 \times 10^{-13}$ GeV for Δa_X, and $\pm 2.7 \times 10^{-13}$ GeV for Δa_Y.

TABLE I: Contributions to the systematic uncertainty.

Contribution	${\rm Re}\,\xi\,y - {\rm Im}\,\xi\,x$	Δa_X (GeV)
Absorption	± 0.0017	$\pm 0.0 \times 10^{-13}$
Split sample	± 0.0000	$\pm 1.7 \times 10^{-13}$
Fit variant	± 0.0012	$\pm 1.2 \times 10^{-13}$
Cut variant	± 0.0036	$\pm 1.4 \times 10^{-13}$
Total	± 0.0041	$\pm 2.5 \times 10^{-13}$

TABLE II: Contributions to the systematic uncertainty.

Contribution	$(\Delta a_0 + 0.6\,\Delta a_Z)$ (GeV)	Δa_Y (GeV)
Absorption	$\pm 0.4 \times 10^{-13}$	$\pm 0.1 \times 10^{-13}$
Split sample	$\pm 0.0 \times 10^{-13}$	$\pm 2.2 \times 10^{-13}$
Fit variant	$\pm 0.4 \times 10^{-13}$	$\pm 0.7 \times 10^{-13}$
Cut variant	$\pm 2.0 \times 10^{-13}$	$\pm 1.4 \times 10^{-13}$
Total	$\pm 2.1 \times 10^{-13}$	$\pm 2.7 \times 10^{-13}$

We have performed the first search for CPT violation in neutral charm meson oscillations. We have measured the complex CPT violating term ξ as a function of the mixing parameters x and y. We find ${\rm Re}\,\xi\,y - {\rm Im}\,\xi\,x = 0.0083 \pm 0.0065 \pm 0.0041$ which lead to a 95% confidence level limit of $-0.0068 < {\rm Re}\,\xi\,y - {\rm Im}\,\xi\,x < 0.0234$. As a specific example, assuming $x = 0$ or ${\rm Im}\,\xi = 0$ and $y = 1\%$, one finds ${\rm Re}\,\xi = 0.83 \pm 0.65 \pm 0.41$ with a 95% confidence level limit of $-0.68 < {\rm Re}\,\xi < 2.34$. Within the Standard Model extension we set three new independent limits on the coefficients of Lorentz violation of $(-3.7 < \Delta a_0 + 0.6\,\Delta a_Z < 6.5) \times 10^{-13}$ GeV, $(-9.4 < \Delta a_X < 5.0) \times 10^{-13}$ GeV, and $(-9.3 < \Delta a_Y < 5.1) \times 10^{-13}$ GeV, assuming the mixing parameters x and y are 1% and the strong phase between doubly Cabibbo suppressed and Cabibbo favored decays is 15°.

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[22] Sidereal time is a time measure of the rotation of the Earth with respect to the stars, rather than the Sun. Sidereal day is shorter than the normal solar day by about 4 minutes.
[23] The result is very sensitive to the choice of mixing parameters and the phase